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EXPERIMENTAL INVESTIGATION ON OIL SHALE CIRCULATING FLUIDIZED BED BOILER

JIANG XIUMIN
LIU DECHANG
CHEN HANPING
ZHENG CHUGUANG
Huazhong University of Science and Technology,
National Laboratory of Coal Combustion
Wuhan, 430074, P. R. China

QIN YUKUN
Harbin Institute of Technology
Harbin, 150001, P. R. China

The paper introduces an oil shale fired circulating fluidized-bed (CFB) boiler of the capacity 65 t/h. Fundamental research and boiler operation have shown such its advantages as high combustion efficiency, flexible load adjustment, low pollution, combustion stability and simple operation control. Successful development of this boiler will provide new ways to use oil shale as power-generating fuel efficiently and friendly to the environment and also offers a platform for developing large-scale CFB boilers utilizing oil shale.

Introduction

Resources of oil shale are second to coal in terms of heat value and 5.4 times more than those of oil [1, 2], corresponding to 475 billion tons if converted to shale oil. Consequently, oil shale has great potential to be used as fuel in power industry.

The difficulties associated with technology and environmental protection have restricted the large-scale utilization of oil shale as an energy resource [3, 4]. In China, the newly developed 65-t/h pilot CFB boiler has shown a promising way to burn oil shale on a larger scale. There are three such boilers currently in successful operation in Huadian city, Jilin Province, P. R. China.

Project Description

Main Design Data of the Boiler:

Nominal capacity	65 t/h
Steam pressure	5.29 MPa
Steam temperature	450 ºC
Feed water temperature	150 ºC
Stack temperature	153.4 ºC
Preheated air temperature	240 ºC
Design thermal efficiency	≥85 %
Oil shale grain size	0–10 mm

Oil Shale Characterization

The data on the Huadian oil shale analysis are as follows: contents, as received basis, wt%: carbon 20.4, hydrogen 2.54, oxygen 9.82, nitrogen 0.505, sulfur 1.015, ash 54.82, moisture 10.9; volatiles (dry ash-free basis) 80.7; net calorific value 8,374 kJ/kg. Ash composition, %: SiO_2 55.18, Al_2O_3 17.20, Fe_2O_3 9.73, CaO 12.44, MgO 2.66, $Na_2O + K_2O$ 2.52; deformation temperature 1077 ºC, softening temperature 1153 ºC, fusion temperature 1220 ºC.

Grain Size and Fluidization Velocity

Due to oil shale physical structure its particle shows the shape of sheet after grinding, and this can cause a short path and dead zones in the fluidized bed. This problem can become serious with the increase in the particle size. In the case of the boiler under investigation, the particle size is restricted to 0–10 mm. The air velocity at the nozzle hole of air gap is 58.9 m/s, and the outlet velocity at the air guiding devices is 5.7 m/s. The fluidization velocity in hot condition is around 4.5–6.5 m/s. The operation practice proved that the correct combination between air distribution structure and fluidized bed parameters could raise the fluidization quality of oil shale and ensure the even particle distribution as well as reasonable mixing in the dense bed. No deposition of large sheet-shape particles in the bottom of the bed was noticed.

Combustion Features and Design Principles

The carbon and hydrogen ratio in oil shale is about 6.2–8.5 (this value for Huadian oil shale is about 8) compared to about 13 for coal, and its content of volatiles is much higher than that of coal as well. As a result, the combustion features of oil shale differ from those of coals. The main feature of oil shale combustion is that the containing in it energy is released mainly through the combustion of volatiles. The combustion ratio in the dense phase zone is lower than 50–60 %. The effective and reasonable organisation of particle circulation and burning-out of fine particles during their residence period in the furnace is extremely important.

Combustor Temperature

The temperature in the CFB boiler combustor, one of the most important design parameters, largely affects the emission of pollution gases, the efficiency of desulfurization and slagging. 850 ºC was selected after comprehensive considering of combustion efficiency, reduction of SO_x and NO_x emission and prevention of caking.

Circulation Ratio and Burning-out Properties

When the temperature increases rapidly, the chemical structures are broken and a large amount of volatiles is released. This would cause high pressure inside the oil shale particles and produce some paths for volatiles to escape them. Ignition starts homogeneously due to the rapid release of combustible volatile compounds. The ignition and combustion of char follow the combustion of volatiles. However, ash whose content is as high as 55 % could form an ash shell around the burning particle and reduce the conversion of carbon. Circulation of particles is essential for the char burning-out. Based on the research [5], a circulation ratio of 6 has been selected.

Self-Desulfurization Capability

Sulfur present in oil shale is converted into gases (mainly SO_2 and some SO_3). However, not all the sulfur is released into the atmosphere. Some sulfur reacts with alkaline materials such as CaO, MgO, Na_2O, and K_2O remained in ash. Sulfur content of Huadian oil shale is 1.015 % and CaO content is 12.44 %. Consequently, its self-desulfurization ability is quite high. The Ca/S molar ratio is up to 3.839, the sulfur emission can be well controlled without adding any desulfurizing agents.

Bottom Ash – Thermal Loss and Pollution

Huadian oil shale has a high ash content – about 55 %. About 50 % of ash is removed from the bottom of the bed, so its temperature is at the level of the bed temperature. The heat loss with the bottom ash reduces the boiler heat efficiency and pollutes the environment. Water and air are used to cool down the bottom ash to 150 ºC. This enables to raise the heat efficiency by 1–2 % [6].

Boiler Design

The furnace comprises membrane walls and an air distribution device with a bottom grid. The high- and low-temperature superheaters and a convective heating surface are placed in the convective pass. Two concentrated and four dispersed descending tubes connected to the bottom of the steam drum provide circulating water to the water-cooled tubes and convective heating surface, respectively. The economizer and the air heater are placed in the back pass of the boiler. Two cyclones and loop seal are arranged between the convective flue pass and the back pass; two storages for start-up and ash removal are installed outside of cyclones.

The primary air that accounts for 82 % of total combustion air provided by air fan is heated to 240 °C and fed to combustor through bottom grid. The secondary air accounts for 22 % of total preheated air and is fed to the combustor through two side walls of the boiler. The residual 18 % of total combustion air remains cold and is directed to ash coolers to cool and fluidize coarse ash particles.

The air temperature at the outlet of ash cooler may reach 260 °C. Preheated air is supplied to the combustor through side walls as the secondary air. The coarse ash particles are drained out to ash cooler and afterwards the cooled ash will be directed to the ash-removal system. The flue gas containing a large amount of solid fines enters two middle-temperature cyclones and the particles collected by cyclones are transported to the furnace through the loop seal to realize recirculating combustion. The oil ignition system is arranged above the bottom grid. The overall structure of the boiler is shown in Fig. 1. The data on design and operating conditions of the heat transfer surface are shown in Table 1.

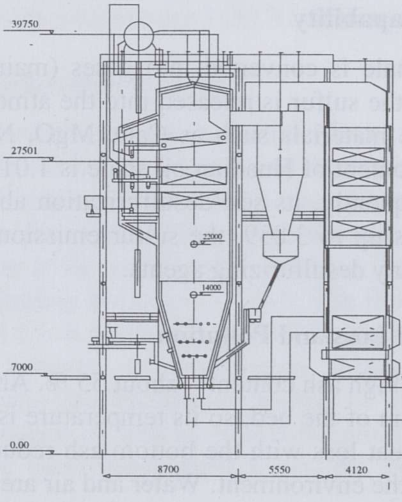

Fig. 1. CFB boiler

Results and Discussion

Start-up Characteristics

Figure 2 shows the changes in the furnace outlet temperature and in the fluidized bed temperature with time. The temperatures are measured at three positions – at the front, back and right side of the combustor. Small differences in temperatures measured at the same time prove a good fluidization quality in bed during the start-up process.

Table 1. **Technical Data of the Heat Transfer Surfaces**

Items	Furnace	High-temperature superheater	Low-temperature superheater	Convection bank	Divert room	Economizer	Air heater
Flue gas temperature, ºC:							
inlet	–	850	775.5	669.9	537	525	287.8
outlet	850	775.5	669.9	537	525	287.8	153.4
Working fluid temperature, ºC:							
inlet	–	340	272.9	–	–	150	20
outlet	–	450	393	–	–	254	240
Velocity, m/s, of:							
flue gas	–	4.34	4.05	4.5	–	7.1	8.9
working fluid	–	19.3	22.3	–	–	–	6.76
Heat transfer coefficient, w/m^{2}K	103.5	81.4	81.2	70.9	–	51.4	18.3
Heating surface area, m^2	245.6	153.1	205.3	449.3	–	793.5	3096
Additional heating surface area, m^2	–	17.1	15.4				
Temperature difference, ºC	576.8	417.5	389.7	330.3	–	196.9	78.4
Absorbed heat, kW/kg	2242	790	985.6	1623.2	118.9	1220.8	677.8
Additional absorbed heat, kW/kg	–	113	303.5	–	–	–	–

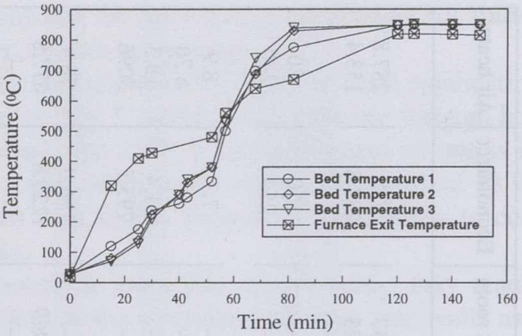

Fig. 2. Boiler start-up from cold condition

Fluidized-Bed Operation Velocity

Figure 3 shows the changes in the fluidized-bed operation velocity and in the pressure in the wind box depending on the boiler load. From these figures it is clear that both the operation velocity and air box pressure increase with boiler load.

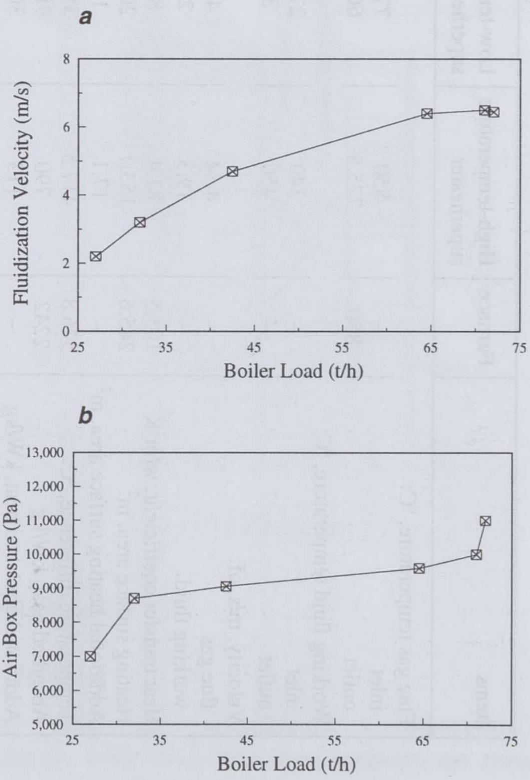

Fig. 3. Relation between boiler load, and (*a*) fluidization velocity and (*b*) air box pressure

Temperatures of Steam and Water

The designed feed-water temperature is 150 °C, and the temperature of the water leaving economiser is 254 °C. Figure 4,*a* illustrates the water temperature change with boiler load and shows that the economiser water temperature can meet the design demand. Superheater is divided into two parts, and a water spray is installed between them to adjust the steam temperature. Figure 4,*b* shows that the steam temperature can reach the design value as well.

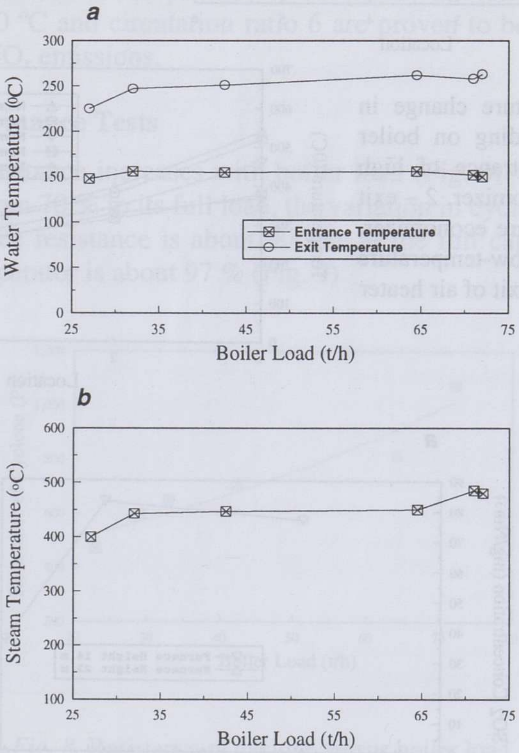

Fig. 4. Relation between boiler load, and (*a*) entrance and exit water temperature and (*b*) superheated steam temperature

Temperature in Different Positions

Temperature changes in the re-circulation system depending on the boiler capacity are shown in Fig. 5. Figure 6 shows the temperature changes in the back pass. Both demonstrate that all these temperatures agree well with the design values when the boiler reaches its full capacity.

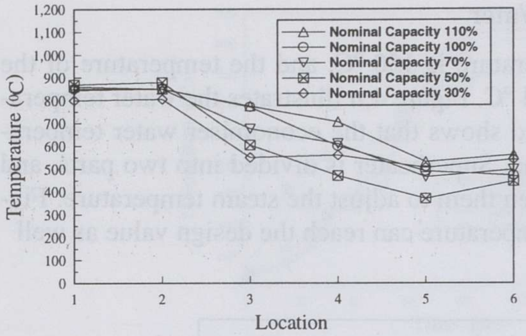

Fig. 5. Temperature change in fly ash circulation loop depending on boiler capacity: *1* – fluidized bed, *2* – furnace, *3* – exit of high-temperature superheater, *4* – exit of low-temperature superheater, *5* – cyclone entrance, *6* – exit of loop seal

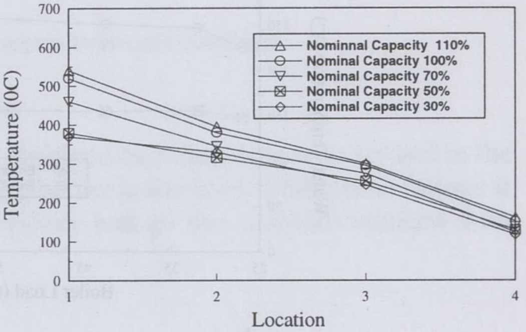

Fig. 6. Temperature change in back pass depending on boiler capacity: *1* – entrance of high temperature economizer, *2* – exit of high-temperature economizer, *3* – exit of low-temperature economizer, *4* – exit of air heater

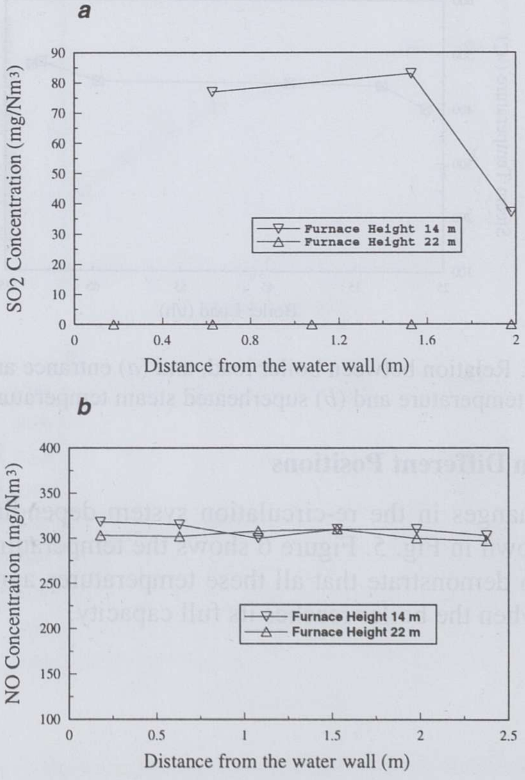

Fig. 7. SO_2 (*a*) and NO_x (*b*) concentrations at different testing points

Emissions of SO_2 and NO_x

A small amount of SO_2 can be observed in furnace at the height of 14 m (Fig. 7,*a*). The content of SO_2 increases towards the walls, however, it is negligible at the height of 22 m. This demonstrates that Huadian oil shale is of great self-desulfurizing ability due to its high Ca/S molar ratio.

Figure 7,*b* shows the NO_x concentration at two heights in furnace at boiler full load. There is almost no change in NO_x concentration both along and across the furnace. The primary to secondary air ratio 60/40, furnace temperature 850 °C and circulation ratio 6 are proven to be effective to reduce SO_2 and NO_x emissions.

Cyclone Performance Tests

The cyclone resistance increases with boiler load (Fig. 8). When the boiler load changes from 70 % to its full load, the variation in cyclone resistance is only 200 Pa. The resistance is about 900 Pa at the full capacity. The total efficiency of separator is about 97 % (Fig. 9).

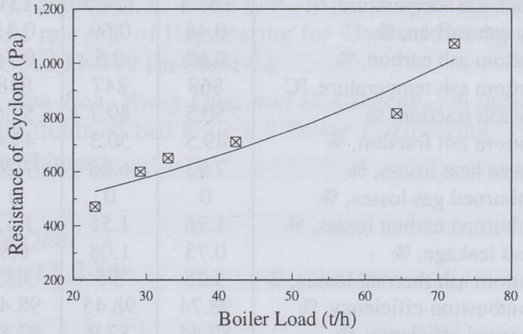

Fig. 8. Resistance of cyclone versus boiler load

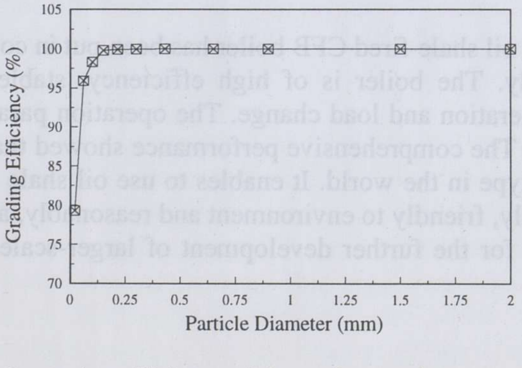

Fig. 9. Separating efficiency of the cyclone under constant load

The re-circulation ratio reflecting the re-circulation times and residence time of different-size particles has a critical role in combustion efficiency. The ratio was arranged to be 6 after comprehensive consideration of combustion and burning-out efficiency, intensity of heat transfer in the furnace, the control over superheated steam temperature and boiler load, operational stability, reliability of particle separation system, abrasion of heat surface, and energy consumption.

Boiler Thermal Efficiency at various capacities is presented in Table 2.

Table 2. **Boiler Efficiency**

Items	Mode 1	Mode 2	Mode 3
Steam capacity, t/h	71.4	48.06	64.74
Steam pressure, MPa	5.1	5.2	5.2
Steam temperature, ºC	441	445.3	449
Net calorific value, kJ/kg	8,083	7,362	7,087
Feedwater temperature, ºC	150	154.3	161
Air temperature, ºC	25.53	12	26.37
Stack gas temperature, ºC	161.8	124.3	151
Fly ash carbon, %	0.48	0.69	0.41
Bottom ash carbon, %	0.62	0.5	0.74
Bottom ash temperature, ºC	868	847	848
Fly ash fraction, %	50.5	49.7	52.6
Bottom ash fraction, %	49.5	50.3	47.4
Waste heat losses, %	7.93	6.86	7.20
Unburned gas losses, %	0	0	0
Unburned carbon losses, %	1.26	1.55	1.53
Heat leakage, %	0.73	1.08	0.8
Bottom ash thermal losses, %	3.25	3.5	3.53
Combustion efficiency, %	98.74	98.45	98.47
Thermal efficiency, %	87.44	87.9	87.83

Conclusions

The 65-t/h pilot oil shale-fired CFB boiler has been put in commercial operation successfully. The boiler is of high efficiency, stable operation, and flexibility in operation and load change. The operation parameters meet the design demand. The comprehensive performance showed that at present it is the best boiler type in the world. It enables to use oil shale as an energy resource effectively, friendly to environment and reasonably, and also to set up a reliable basis for the further development of larger-scale boilers of such type.

Acknowledgements

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